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Computed Tomography and Advanced X-ray  
and Charged-Particle Imaging

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# Computed Tomography and Advanced X-ray and Charged-Particle Imaging

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## Abstract

Computerized tomographic (CT) imaging can provide state of the art techniques to address many industrial nondestructive evaluation (NDE) needs. CT imaging has been developed mainly in the medical field for imaging the human body. Many of the constraints on the type and dosage of radiation used in biological applications are lifted when dealing with the non-destructive evaluation (NDE) of inanimate objects. However, due to differences between biological tissues and industrial materials (e.g., ranges of densities, graininess, refractive indices, etc.), NDE tomography is not necessarily a straightforward extension of medical CT technology. Experimenters are still trying the many modes of the electromagnetic, particle, and acoustic spectra available for illuminating the object. NDE applications of CT include quantitative density measurements, defect detection, defect characterization (density, refractive index, compressibility), and assembly verification. Computer systems, microelectronics, and detector technologies have recently advanced to the point where the development of these systems to do complete 3D inspections in reasonable times is feasible.[1]

Research issues in CT inspection include the long integration times to acquire the data and the large computational burden required to reconstruct the image. Data acquisition time depends on the number of projections, statistics needed for a given signal-to-noise ratio, radiation absorption by the part, imaging geometry, and many other related issues. In some cases, data collection could require several days. Similarly, the computation time required for data analysis depends on the number of projections, scans per projection, output image size, and the reconstruction algorithm used. Here again, some algorithms may require many CPU hours or even days. Generally, the higher the resolution needed for a given part, the more time required in one or both of the above areas. Model-based image reconstruction methods offer two advantages over current techniques: (1) they provide an increased region-of-interest resolution for fixed-cost or time-constrained systems, and (2) they advance the state-of-the-art capability in image resolution regardless of cost.

One of the major limitations of x-ray imaging has always been the lack of effective optical elements. Recently much progress has been made in this field, largely due to efforts in diagnosis of laser-generated plasmas for the laser fusion program both at LLNL and elsewhere.[2] The use of x-ray optics could eventually lead to diffraction-limited imaging which would provide resolution in the range of a few angstroms. In the near term we propose work in demagnifying focal spot sizes, beam collimation, and more modest image magnification.

The problems being addressed by x-ray imaging in NDE are becoming much more sophisticated as we stretch material requirements to the limits. Much of the folklore and radiographers' "rules of thumb" are no longer adequate to answer the questions now being asked of us. Various second-order effects arising within materials undergoing radiographic inspection or in the

experimental apparatus itself lead to aberrations which are indistinguishable from real features. In addition, current *quantitative* data is obtained only by relative means, where the specimen being measured must be compared to reference materials which are closely matched to the specimen in composition and areal density. Since such comparisons are rarely possible, there is therefore a need to develop theoretical radiographic equivalencies between materials (such as single elements, alloys, and mixtures). Further, radiographic procedures, such as dual energy imaging, have the potential of providing element-specific information. For all of these problems, it would be far more efficient to do the experiments computationally rather than in the laboratory in order to better define the parameter space, and then to scale the calculations to the real world with well chosen experiments. To accomplish this we are simulating x-ray imaging experiments using existing LLNL computational radiation transport modelling resources.[3]

The ability to nondestructively inspect materials, parts, and assemblies quantitatively and at high spatial resolution is fundamental to the mission of Lawrence Livermore National Laboratory (LLNL). Over the past several years developments in electronics, computers, and x-ray optics have revolutionized x-ray imaging capabilities. Industrial non-destructive evaluation (NDE) has not kept up with this advance. This project addresses this problem through three major goals: first, to provide a capability for X-ray Computerized Tomographic (CT) imaging to the Laboratory programs in general; second, to investigate and develop new techniques for improving the quality and turn-around time for reconstructed CT images; and third, to develop the models and tools necessary to understand special imaging problems for materials important to LLNL programs.

The first goal will be met by the development of three x-ray CT systems. One system will use low energy x-rays and will be configured for high spatial resolution ( $< 10 \mu\text{m}$ ) measurements. This system will be applied towards the inspection of composite and advanced materials. The second x-ray system will use high energy x-rays and will be configured for moderate spatial resolution ( $\sim 0.2 \text{ mm}$ ) measurements. The high energy system will be used to evaluate closed systems, structural components, castings and advanced materials. The third system will apply planar tomography techniques towards the evaluation of electronic components and metal-metal joints. All three systems will allow us to three-dimensionally inspect a wide variety of parts and assemblies of interest to Laboratory programs.

The second goal will be addressed by incorporating new model-based reconstruction algorithms and fast computer implementations in the data processing stages of CT. Both the accuracy and the speed of the tomographic imaging system will be improved by using *a priori* information based on models of the object being inspected.

To meet our third goal, we will develop techniques in heavy charged-particle (large mass compared to an electron) CT and spectral CT which will allow total electron density and element specific inspection of low-density materials. We will address state of the art techniques in x-ray optics and in radiation transport modelling which promise to have a major impact on x-ray imaging in general.

We believe that it is important to the Laboratory as a whole to have the capability of high resolution and high energy three-dimensional non-destructive part inspection. These capabilities currently do not exist within the nuclear weapons community [4]. The work proposed in this project can move LLNL to the forefront of industrial x-ray and charged-particle imaging.

The scope of work and deliverables proposed in each of these R&D projects will be described in the Technical Discussion of Approaches. Several areas involve outside as well as internal collaborations and will be indicated accordingly.

## Technical Discussion of Approaches

Our work in Computed Tomography and advanced x-ray and charged-particle imaging will be divided into two major areas, one in CT research and development, and the other in advanced imaging research. Each of these areas is further subdivided into several specific projects or phases. The first two are directed at the goal of instituting two tomographic systems, whereas, the last four are more directed at the advanced radiation activities which will support the tomography research and also provide us with unique capabilities in allied areas of radiation transport and analysis.

Computed tomography projects include:

- I. High-resolution and High-energy X-ray CT systems,
- II. Model-based image reconstruction techniques.

Advanced radiation imaging projects include:

- III. Heavy charged-particle imaging,
- IV. X-ray spectral imaging,
- V. X-ray optics for microimaging, and,
- VI. Radiation transport modeling.

### Phase I. High-resolution and High-Energy X-ray CT systems

#### *Objective*

LLNL programs have demonstrated a widespread interest in three dimensional CT imaging. In this project we propose to develop two systems to make this capability routinely available for a broad spectrum of Laboratory needs.

#### *Scope of work*

##### *High resolution system*

In this mainly developmental area we propose to design and build a CT system for inspections at spatial resolutions better than 10  $\mu\text{m}$  or 50 line-pairs/mm. This system will handle small to medium sized parts (< 30 cm and < 100 lbs) and cover an energy range from 1 to 400 keV. A helium flight path will be provided for low-energy (< 10 keV) work. The major CT images produced by such a system will be of small weapons parts (e.g., fire-sets), low-density parts, ceramics, glasses, and composite and advanced parts and materials. The high-resolution x-ray CT system will be based on a 2D Charged-Coupled Device (CCD) detector and a 1D Si(Li) diode detector. We will design the system for 3D imaging at better than one percent contrast sensitivity.

The tasks involved are:

- source selection --  $\mu$ -focus and/or rotating-anode tubes;
- detector design -- CCD and/or Si(Li);
- data acquisition system design -- Sun-3 based;

- mechanical system design.

The system proposed in this area will be very similar to a high-resolution x-ray imaging system currently being built by us for one of the LLNL programs. The major differences between their system and our system are the wider energy range and an option to use the extremely accurate 1D Si(Li) detector.

### *High energy system*

High-energy imaging systems capable of 3D inspection of assemblies containing high-Z materials (e.g., plutonium, uranium, etc.) are of great importance to the Weapons Program. Therefore, we will build, in collaboration with Sandia National Laboratory, Albuquerque (SNLA) and Los Alamos National Laboratory (LANL), a high energy system with a spatial resolution of approximately 500  $\mu\text{m}$  and a contrast sensitivity of less than one percent. The high-energy CT system will have an x-ray energy range from 400 keV to 8 MeV and will handle objects up to a meter in diameter and weighing up to several hundred pounds.

The tasks involved are similar to those for the high-resolution CT system. However, in addition to the x-ray tubes mentioned above, we will use both linear accelerators (4 MeV and 8 MeV available in NDE) and radioisotope sources (e.g.,  $^{60}\text{Co}$  with 1.2 and 1.3 MeV gammas). In this proposed development, the detector design will be the most critical item; a collaboration with SNLA and LANL will facilitate this design. The challenges in high-energy CT are greater than those in high-resolution CT, since this area is not as well explored.

### *Deliverables*

The major deliverables in this project are two operational CT systems capable of routinely performing high-resolution, quantitative evaluation of materials, parts and assemblies. In addition, we will gain an understanding of the resolution and energy limits obtainable with such CT systems.

## **Phase II. Research in Model-based Reconstruction Techniques**

### *Objective*

We will investigate the use of *a priori* information and modern parallel computer architectures in the reconstruction of CT images. These techniques will be useful in improving the image quality and in reducing the time required to reconstruct images (by reducing both the volume of data collected and the amount of computations required for reconstruction).

### *Scope of work*

The types of available information which can be useful in CT include full mechanical specifications of part dimensions (e.g., CAD/CAM specs.), expected densities, elemental make-up, wavefront interference properties, and estimated statistical models of inhomogeneities. This effort will affect several tomographic techniques:

- Limited-view tomography In some cases, it is impossible to acquire projections on the full 180-degree arc required for reconstruction of the image. Noise induced by incomplete data causes distortions in the image, especially if flaws are present. By

incorporating model information for specifying unobserved data, the signal-to-noise ratio can be improved for reconstructed tomograms.

- Region-of-interest tomography This is related to the limited-view problem. Suppose there is a small region in an object that is important to be displayed at high resolution, while the rest of the object is not so critical. One would prefer to minimize the data collection time by intelligently scanning at the few key locations which would elicit the most information about that small region. In addition, model-based schemes could help design optimal source and detector locations and projection angles, as well as enhance the reconstruction as in limited-view tomography.
- "Near real-time" tomography It is often desirable to obtain a global view of a region (perhaps at low resolution) before embarking on a time-consuming high-resolution run. Using model information, simple images could be obtained quickly so that human operators can get feedback for setting up the next scan.
- Template matching For production parts, it is common to have a sample part that is known to be "good" in some sense (*e.g.*, without flaws). This relatively flawless part can be tomographically inspected prior to routine testing of assembly-line parts. The system now has a template for image comparisons. This somewhat simplifies the collection strategy as it can be optimized for the part geometry. Processing can also be performed in the projection, also known as Radon, domain thereby eliminating the problem of time-consuming reconstruction calculations and the need to rotate the template. There is an indication, also, that some of these algorithms can be downloaded to fast dedicated processors (array processors or image processing boards). This idea can also be applied to "multi-media CT" where different modalities are used (*e.g.*, x-ray vs. proton radiation; low-frequency vs. high-frequency; wide-band vs. narrow-band) and compared on a single part. The difficulty lies in registration - identifying corresponding locations in the two images acquired by different instruments at possibly different magnifications.

A joint U.C. Davis - LLNL research project is being started which will connect directly into this task. The project involves the development of Radon transform-based algorithms and fast computer architectures. The Radon transform provides the theoretical basis for tomography algorithms, but is not limited to CT. A machine will be designed and built which will take advantage of inherent parallelism at the Radon transform, and thereby compute it rapidly. The machine would be 10 to 100 times faster than existing hardware used for tomography. It will implement a number of projection (forward Radon) and reconstruction (inverse Radon) algorithm families in two- and three-dimensions.

Each of the above techniques will be studied in the context of the commonly inspected parts at LLNL. Our approach will proceed as follows:

- Identify or fabricate test objects which have high quality models associated with them.
- Incorporate these models into the reconstruction (initially Algebraic Reconstruction Techniques, ART) algorithm.
- Study computer algorithms and architectures that are appropriate for this work.
- Prototype Radon techniques on SPRINT architecture[5].
- Suggest techniques to be used in improving reconstructive image quality.

## ***Deliverables***

- Algebraic reconstruction technique incorporating part models,
- Techniques for Radon transform operations on the SPRINT architecture, and
- Joint proposal with UC Davis to an outside funding agency for development of a Radon transform architecture machine.

## **Phase III. Research in Heavy Charged-Particle Computed Tomography**

### ***Objective***

Currently, the characterization of low-density materials is less complete than desired. We are able to determine the density with an accuracy of a few percent, and spatial distribution to ~0.5 mm, but have been unable to develop methods of reliably measuring spatially-resolved total electron densities. Heavy charged-particle (large mass compared to an electron) computed tomography (CT) holds the promise of measuring total electron densities with an accuracy of better than one percent and a spatial resolution to better than 10  $\mu\text{m}$ . In addition, the Heavy charged-particle CT data are sensitive indicators of microstructure on a much finer scale. We will first discuss the CT measurements and secondly discuss possible applications and tasks involved.

### ***Scope of work***

Heavy charged-particle computed tomography is based on the determination of the integrated electron density by measuring the energy loss of the heavy charged particles which pass through a specimen. The energy loss formula for heavy charged particles is given by :[6]

$$-\frac{dE}{dx} = n_e(x,y,z) \cdot F(I(x,y,z),\beta), \quad (1)$$

where:  $n_e(x,y,z)$  is the number of electrons in a unit volume at  $(x,y,z)$ ,  
 $I(x,y,z)$  is the ionization potential of the medium at  $(x,y,z)$ , and  
 $\beta$  is the proton velocity in units of light velocity.

As seen in Equation 1, the ionization loss incurred by heavy charged particles as they pass through a medium is proportional to the electron density  $n_e(x,y,z)$  and the ionization potential of the medium. Since the ionization potential is roughly proportional to the atomic number of the material, the energy loss depends on the electron density  $n_e(x,y,z)$  and the atomic number,  $Z$ , of the material. From Equation 1, the following equation for the integrated electron density is obtained:

$$\int_{-\infty}^{+\infty} n_e(x,y,z) dx = \int_{E_o}^{E_i} \frac{dE}{F(I(x,y,z),\beta)} \quad (2)$$

where  $E_{i,o}$  is the energy of the incident, outgoing charged particle respectively.

Knowledge of  $I(x,y,z)$  in addition to the values of  $E_i$  and  $E_o$  is required to perform the integration of Equation 2. For materials constituting a small difference in ionization potential the constancy of  $I(x,y,z)$  can be considered a good approximation, taking into account the weak dependence of the energy loss on the ionization potential. Therefore, the integrated electron density can be derived from the knowledge of  $E_i$  and  $E_o$ . It is important to note, that in addition to the total electron density information, the shape of the residual energy spectrum is a direct measurement of the uniformity of the distribution of electrons in the material. We believe that these unique imaging characteristics of charged particles will be extremely beneficial to the computed tomographic imaging of low-density materials.

LLNL is building a new Tandem Van de Graaff Accelerator Facility at the Laboratory that will produce a beam ideally suited for this work. Sandia National Laboratory, Livermore (SNLL) is building a beam line/ion microprobe which will be installed in the new accelerator facility. We will be collaborating on the heavy charged-particle CT research and development with SNLL, and LLNL Programs.

The tasks involved will be as follows:

- development of a computer interface to read data from the SNLL data acquisition system;
- develop reconstruction techniques to produce images from the energy loss information;
- develop models to determine material microstructure based on the distribution of the residual energy spectrum;
- research and development of new reconstruction techniques to produce images of the uniformity of the total electron distribution from the shape of the residual energy spectrum; and
- develop models and techniques for combining charged-particle and x-ray data synergistically to characterize the electron density of materials.

### ***Deliverables***

- A capability for CT imaging using heavy charged-particles at the new LLNL Tandem Van de Graff facility.
- An understanding of the usefulness of charged-particle imaging for the evaluation of low-density materials.
- An understanding of the combination of information from multiple imaging techniques.

## Phase IV. X-ray Spectral Imaging Research

### *Objective*

We will investigate the use of energy-selectable detectors for imaging single elements in multi-element components.

### *Scope of Work*

When we do a typical x-ray CT scan we measure the total number of x-ray photons transmitted through our specimen compared to the total number incident on the specimen. This technique gives us a total x-ray attenuation for the particular source to detector path (or paths) being measured. When we reconstruct our image we assume that the x-ray photons all have a single energy. In most cases though, our source is actually an x-ray tube which emits a continuous spectrum of energies. This invalid assumption causes errors in our total attenuation measurements and therefore in our reconstructed images.

If we can actually measure the spectral distribution of both the incident and transmitted x-ray beams we can use this information to correct these errors. By prefiltering the polychromatic source we can choose a narrow portion of the spectrum thus simulating a monoenergetic beam which we can then use for imaging without introducing spectral artifacts.

Since our x-ray tube sources emit a continuous spectrum we can also effectively simulate a tunable x-ray source by using selectable narrow portions of the spectrum. By imaging a given specimen at multiple energies we can acquire information on the elemental distribution of a part which will be extremely interesting to a variety of LLNL programs.

Assume that we have a part which consists of a mixture of two elements. Each element has discontinuities in its x-ray absorption spectrum which correspond to its characteristic spectral lines (see Fig. 1 below). If we measure the x-ray transmission at two energies -  $E_1$  and  $E_2$ , then the attenuation of element one will change a great deal because of the discontinuity while that of element two will change very little. Therefore, if we reconstruct images acquired at these two energies and then subtract them, the difference image will give us the distribution of element one alone.

Over the past year we have developed a pencil-beam (single source-detector) system which will allow us to measure a complete spectrum at each point. We have used the system only with radioisotope sources which have a small number of discrete energies in order to do quantitative density measurements. With the addition of a continuous spectrum x-ray tube source the PBCAT system will be able to make the type of measurements described above. We will use this system to develop the techniques described above for a variety of materials. The major tasks involved are the interfacing of the tube source to the pencil-beam system, the development of simulated monochromatic imaging, and, based on these tasks, the development of elemental imaging for materials, parts, and assemblies.

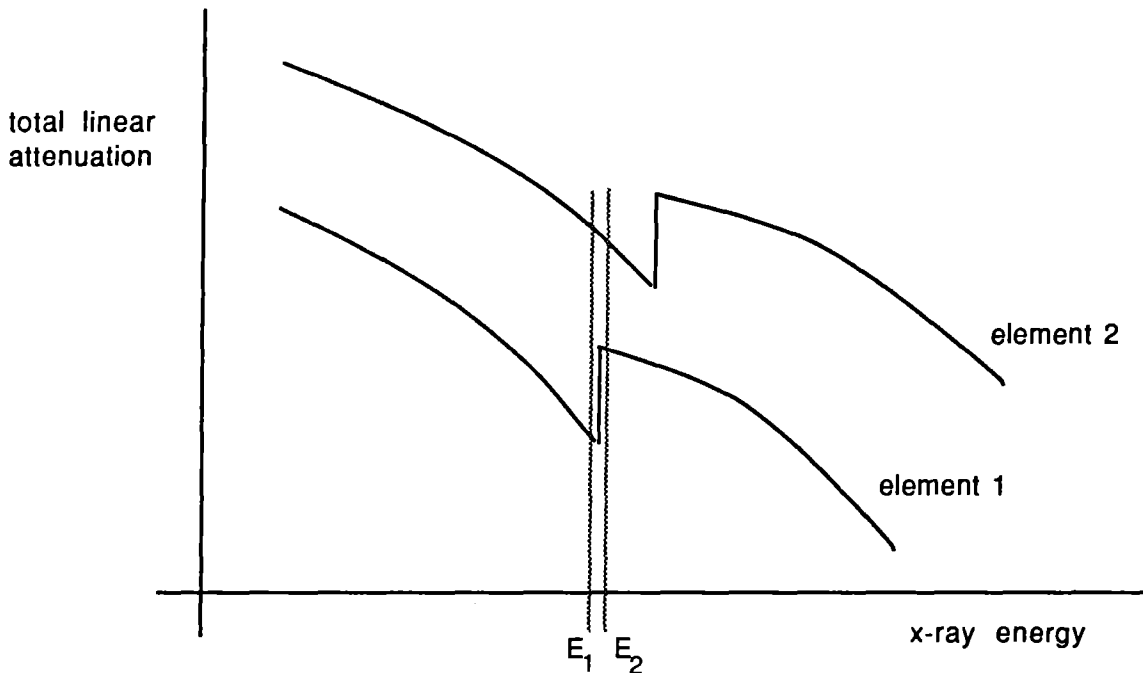


Fig. 1 X-ray attenuation versus energy for two constituent elements.

### ***Deliverables***

- Techniques for simulating monochromatic imaging on the pencil-beam CT system (PBCAT) using a polychromatic source.
- An understanding of the problems and limitations of elemental imaging of interesting materials, parts, and assemblies using polychromatic sources.
- Techniques for elemental imaging on PBCAT.

## **Phase V. X-Ray Optics for Microimaging Applications**

### ***Objective***

Our objective is to obtain a sufficient x-ray flux from a fine focal spot so that many measurements which now can only be contemplated at synchrotron light sources may be made in the laboratory. The means to this end is to design and build x-ray focusing optical elements. Applications include x-ray fluorescence microanalysis and imaging, tomography, and photoacoustic imaging.

### **Background**

Various forms of imaging which utilize x-rays of 25 keV or less have become increasingly important to the LLNL Weapons programs and other LLNL programs such as Lasers and Special Projects. Areas where challenging low energy x-ray imaging is being required include tomography, fluorescence, Compton scattering, and gauging. These methods all share the same

need for the highest possible photon fluxes on small areas in order to achieve reasonable data acquisition times for high-spatial-resolved imaging.

We need to image subsurface details and flaws with resolutions on the order of a micrometer. By collimating beams from standard x-ray sources, spot sizes of about 100 micrometers can be achieved with sufficient flux to make some useful measurements. Illuminated spots of 10 micrometers or less require that experiments be done at synchrotron facilities, which are limited in availability and where classified work is usually not possible.

Recent advances in materials fabrication technology has lead to the successful construction and use of x-ray focusing optical elements. Because photons are gathered over an extended area and brought to focus on a tiny spot, several orders of magnitude increase in flux are obtained compared to ordinary collimated beams. Either grazing incidence specular reflection or low-angle x-ray diffraction can be employed. Jim Underwood and his colleagues at the LBL Center for X-Ray Optics have successfully employed Kirkpatrick-Baez optics to focus 10 keV radiation onto spots of 10 micrometers. Spherical optical elements were used. The potential for energies as high as 25 keV with spot sizes as small as one micronmoter is present.

The mirrors are made by the deposition of alternating layers of high and low atomic number elements, such as tungsten and carbon, onto a curved surface substrate which has been machined and polished to a smoothness of about three angstroms. At a grazing incidence angle, soft x-rays are reflected as from a mirror (see fig. 2). At higher angles, higher energy x-rays

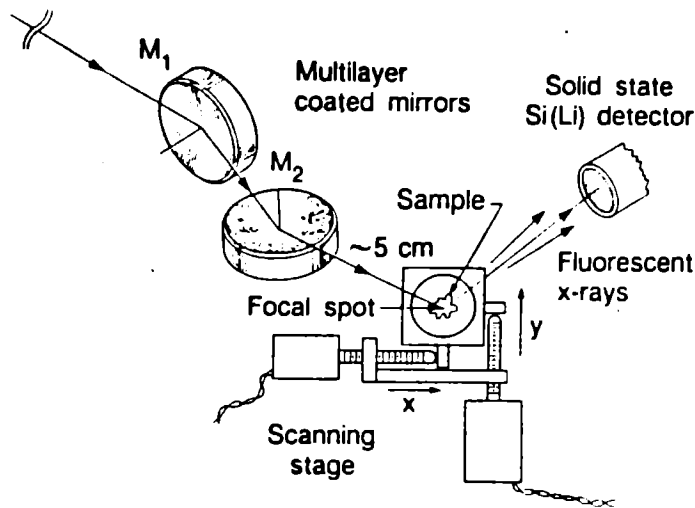


Fig. 2 Schematic diagram of the use of multilayer mirrors for x-ray imaging.

are diffracted in accordance with Bragg's Law:

$$n \lambda = 2d \sin \theta ,$$

where  $n$  is the order,  $\lambda$  is the wavelength and  $d$  is the sum of the thickness of one-layer pair of the two components. By decreasing the thickness of the layers, higher energies at higher angles can be diffracted.

We presently have ongoing R&D efforts in microfluorescence imaging and tomography which can benefit from the higher photon fluxes made possible by these recent developments. We have also done exploratory experiments on x-ray induced photoacoustics at the Stanford Synchrotron Laboratory. Much more rapid progress could be made if we could do experiments using conventional x-ray sources in our own laboratory. The LBL group at the Center for X-Ray Optics has the expertise to design and construct the lenses. LLNL has the capability to do the ultra-high precision machining to make the curved surfaces with angstrom smoothness required of the optical elements.

### ***Scope of Work***

We propose to study the limits of x-ray optics with regard to "light" gathering power at the highest possible energy. We will then proceed to construct lens systems with focal spots of 1-10 micrometers. These lenses will be tested with regard to their operational characteristics and applications.

The tasks involved are as follows:

- Design two lenses with the largest possible diameter for different focal lengths with the smallest achievable interlayer spacing. Eliminate spherical aberrations.
- Machine substrates. Build mirror supporting structures and apparatus.
- Characterize the performance of the lenses and test capabilities, particularly with reference to imaging techniques such as microfluorescence, photoacoustics, and tomography.
- FY89 will emphasize instrumentation for specific applications, with continuing lens research.

### ***Deliverables***

We will have advanced the new field of x-ray optics to higher energies and fluxes with the elimination of spherical aberrations. We will have in our possession lens systems which have been characterized with regard to their performance characteristics, and will have initiated their useful applications.

### ***University Contracts***

We will work with the Lawrence Berkeley Laboratory Center for X-Ray Optics for the design and construction of the optical systems.

## **Phase VI. Radiation Transport Modeling**

### ***Objectives***

We seek to understand and overcome the various aberrations, abnormalities, and non-linearities which plague radiographic measurements and x-ray imaging by using newly acquired and evolving computational tools. In order to do so, we will expand the computer codes to include photoelectrons produced by the incident radiation, an important contribution to Laboratory resources. We will apply models of the interactions to improve the visual display of images and

correct intensities for quantitative measurements. By understanding the contributions made by system components, we will be able to design experimental facilities which minimize adverse effects.

## *Scope of Work*

Radiographic inspection of parts and materials is one of the most basic kinds of nondestructive testing and evaluation. The NDE Section has strong ties with laboratory programs such as Weapons, SDI, and Lasers where we provide both material characterization and inspection for flaws in parts ranging from low atomic number, low density organic materials to special nuclear materials.

LLNL leads the world in computational modelling of physical phenomena using supercomputers. We propose to both utilize and improve these existing capabilities to solve difficult problems in inspection of materials of programmatic interest. Such secondary effects as scatter, fluorescence, and secondary electron emission become very important due to the stringent imaging requirements imposed. These effects have never been quantitatively studied in the context of x-ray imaging. By doing these experiments computationally, we can independently study each parameter without interference from other effects. Actual laboratory experiments can then be done to verify the observed effects.

As a group, we have the relevant knowledge and experience to undertake a systematic study of the various interactions of radiation with materials in these measurement systems, to use the computational tools which exist, and to develop them where they are lacking. We have wide-ranging experience and publications in x-ray fluorescence, radiation gauging, systems design, x-ray and neutron radiography, tomography, nuclear physics and chemistry, scientific simulation, and user-interface programming.

The tasks proposed for FY '88 are:

- Add photoelectrons and their induced photons to a Monte Carlo transport code We will work in close conjunction with Tom Wilcox and Ed Lent in L Division, who are the authors of COG[3], a widely used radiation transport program.
- X-ray tube spectral output calculations Verify for sub-50 keV region for common x-ray tube anodes, and extend to higher energies and include all characteristic lines as appropriate
- Film and detector response calculations and verification
- Model calculations of materials of programmatic interest A. Material equivalence calculations, for instance, plastics, high explosives, aluminum alloys, steel alloys, precious metals, penetrameters (Some of these are needed to quantify models, and others for parameter optimization) B. Dual energy radiography --- Contrast simulation, optimization and quantification for mixtures and multi-component devices
- Monte Carlo model of radiography facilities Model cabinet and typical radiation measurement facilities. Propose facility modifications to improve (or reduce) extraneous effects of radiation scatter.
- Dissimilar material interface studies Study edge effect on apparent areal densities with respect to Z, tube operating parameters, atmosphere, fixturing, etc. Characterize apparent dimensional changes (ie, undercutting) resulting from scattering effects.

- Unsharpness Some contributions to fuzzyness of images, such as geometrical considerations, are well understood. Others, such as system and specimen scatter, source non-uniformity, and various operating parameters are only vaguely understood and will be studied in this task.

## ***Deliverables***

Reports and recommendations will be made to the programs as this work progresses. Summaries and suggestions for future work will be made in the last period. Specific accomplishments which we expect include:

- Verified x-ray tube spectral output calculations. Files of photon flux as a function of energy are the necessary front end for radiation interaction calculations, from the most simple back-of-the-envelope estimates to complex simulations such as Monte Carlo calculations.
- The addition of photoelectrons and their resulting bremsstrahlung to the Monte Carlo simulation code COG. This is a Laboratory-wide (and beyond) resource for those who need to accurately calculate radiation shielding, design instruments, etc. as well as our own specific interests in NDE radiation measurements. More realistic and accurate simulations for a wide range of applications will thus result.
- Verified film response functions with respect to the energy of the x-ray photons. Because of its extremely high density of information, film remains an extremely important x-ray detector. This is the required back end of radiography simulations.
- An investigation of new radiographic methods, such as dual energy (or multiple energy) radiography which may lead to specific component imaging practices.
- We will have brought understanding and mitigating solutions to several nagging radiographic problems which have remained intractable until now.

## ***Consultants***

We have had a productive relationship with Prof. Bill Cook and his student Ted Miller at the University of Houston. They have produced a program called "Radiographer's Helper" which is used to guide the experimentalist in selecting experimental conditions. We expect to extend this work from the present qualitative considerations to some of the quantitative issues raised above.

## **Program Organization**

The ability to nondestructively inspect materials, parts, and assemblies quantitatively and at high spatial resolution is fundamental to the mission of Lawrence Livermore National Laboratory (LLNL). Over the past several years developments in electronics, computers, and x-ray optics have revolutionized x-ray imaging capabilities. Industrial non-destructive evaluation (NDE) has not kept up with this advance. This project addresses this problem through three major goals: first, to provide a capability for X-ray Computerized Tomographic (CT) imaging to the Laboratory programs in general; second, to investigate and develop new techniques for improving the quality and turn-around time for reconstructed CT images; and third, to develop the models and tools necessary to understand special imaging problems for materials important to LLNL programs.

The Computed Tomography and advanced x-ray and charged-particle imaging project is one of two major efforts proposed for the NDE Thrust Area. It is divided into six principal project activities, each having their own objective and scope, but fitting into the overall goal of the total effort. Each is important in its own right, however, the synergy of these projects will result in capability unparalleled in the country. The primary activities of this project are expected to be completed at the end of FY89 with specific research activities continuing in FY90.

This project complements several others proposed in the Remote Sensing, Imaging, and Signal Engineering (RISE) thrust area and in the New Initiatives thrust area. Projects in multidimensional data analysis, diffraction tomography, and VLSI algorithm implementation are closely related. We plan to collaborate extensively with all of these efforts.

Many needs exist at LLNL for quantitative, high-resolution 3D imaging. As we move further into the development of modern weapons systems (in particular, nuclear-directed energy weapons) the inspection demands placed on materials, parts, and assemblies become more stringent. Therefore, the importance of a thorough nondestructive inspection of these systems will also increase. The following list gives some examples of important programmatic inspection applications:

- X-ray laser component and assembly inspection  
(currently requires a variety of inspection techniques);
- 3D inspection of high explosive assemblies  
(currently done destructively and by multiple radiographs);
- 3D inspection of radioactive shipping containers for Safeguards Technology Program  
(currently done by real time radiography);
- evaluation of weapons assemblies for the test program  
(currently done by radiography);
- evaluation of foams fabricated by the Chemistry Division for A-Division  
(currently done by destructive examination of samples and radiography);
- stockpile evaluation  
(currently done by variety of inspection techniques including radiography);
- fireset evaluation  
(requested by Pantex, currently done by radiography);
- Z-division applications  
(numerous methods employed, new methods actively sought);
- LIS ceramic laser tube inspection  
(light transmission inspection).

As seen from these examples the needs reach across many programs. They involve imaging requirements which range from spatial resolutions of millimeters to less than a micrometer. Densities of materials range from extremely low-density foams to high-density assemblies. A broadly based project which addresses both the specific program needs as well as general Laboratory needs is required.

## **Personnel qualifications**

Harry E. Martz: Non-Destructive Evaluation Section, Lawrence Livermore National Laboratory. Ph. D., Nuclear and Inorganic Chemistry, The Florida State University. Dr.

Martz's primary technical interests are in the application of x- and gamma-radiation, and charged-particle methods for the characterization of materials, including but not limited to tomography, gauging and radiography. Currently, he is assigned to the lead engineer role in the characterization of materials for the SDI's X-ray Laser Program and coprinciple investigator of the CT R&D Project. Dr. Martz (and associates) has recently completed preliminary proof of principle studies in high resolution tomographic systems for the precise (50  $\mu$ m) 3D characterization of materials. From 1982-1986 he was a participating guest at Lawrence Livermore National Laboratory in the area of charged-particle transmutation reactions, and perturbed angular correlation measurements in the Nuclear Properties Group, Nuclear Chemistry Division. He has a number of publications/ presentations in the area of x-ray imaging, tomography and nuclear chemistry.

James M. Brase, Imaging Project Engineer, Non-Destructive Evaluation Section, Lawrence Livermore National Laboratory. B.S.E.E., Iowa State University, MSEE, UC Davis. Mr. Brase's primary technical activities have been associated with the development of imaging systems for application to quantitative nondestructive evaluation and material characterization systems and analysis. Among his accomplishments include the principal investigator on the development of IMPS and View computer codes -- large scale image processing systems for the analysis and display of multidimensional arrays of data. In particular, the View code was developed for the 3D characterization of high resolution tomographic images and for the analysis of Strategic Defense Initiative Organization (SDIO) related data. Mr. Brase was also responsible for the development of a general purpose x-ray film digitization system for the precise quantitative characterization of material density, uniformity and defects from x-ray film data.

Mr. Brase's current technical activities have been associated with the development of a high resolution computed tomography system for the precise 3D characterization of low density materials. As coprincipal investigator for Computed Tomography Research Project, he is also responsible for development of general purpose CT systems for LLNL applications.

Prior to his work on imaging and tomography, Mr. Brase was involved with the development of the computer interfaces, data analysis, and robotic manipulation of the 14 axis Ultrasonic Test Bed. This state-of-the-art ultrasonic inspection system has the capability to move 14 axis independently to precisely scan complex geometries. Mr. Brase was instrumental in the software and hardware design and in bringing this system on line.

Richard W. Ryon, Lead Engineer, Radiation Measurements, Nondestructive Evaluation Section, Lawrence Livermore National Laboratory. B.S., Chemistry, University of California, Santa Barbara. Mr. Ryon's technical activities are directed toward the application of x-ray measurement techniques, such as fluorescence and Compton scattering to the field of nondestructive evaluation. By joining chemical analysis techniques to nondestructive characterization of materials, he was able to develop methods to determine density and uniformity of specific elemental constituents within low density materials. He has been recognized for his contributions to x-ray analysis, particularly for his development of polarized x-ray sources. He was the lead Plenary Lecturer at the Denver X-Ray Conference in 1981, and was invited to lecture at the Goteborg (Sweden) Conference on X-Ray Analysis. Recent research was directed toward the development of x-ray fluorescence imaging equipment with resolution not previously attained. It was for the successful development of this capability that he and his colleagues Monte Nichols and Dale Boehme at Sandia received an IR-100 award in 1986. His current research activities include the numerical modeling of x-ray inspection and x-ray machine spectral output analysis, and in x-ray optics for the development of bright sources for nondestructive characterization.

Mr. Ryon worked for Shell Oil in Southern California prior to joining LLNL's Chemistry department in 1964. Most of his career has been spent working as an analytical chemist in such

areas as nuclear magnetic resonance, chromatography, and x-ray fluorescence. He has also worked in the area of isotope separation by electromigration. After 1974, Mr. Ryon was responsible for the x-ray fluorescence analysis laboratory.

Stephen G. Azevedo graduated with his B.S.E.E. degree from U. C. Berkeley in 1977 and received a masters in E.E. and Biomedical Engineering from Carnegie-Mellon University in 1978. He has been working since then at the Lawrence Livermore National Laboratory in computational signal and image processing research. His interests have been in the areas of algorithms, numerical methods, languages, display techniques, and inspection imaging. He was co-author of the SIG signal processing program. Most recently he has been working on ultrasonic tomography experiments and model-based methods for image reconstruction for Nondestructive Evaluation (NDE).

Stephen received a masters degree in Computing Science at U. C. Davis in 1986 where he is continuing his studies for a Ph. D. in the field of model-based reconstructive imaging. He is a member of Tau Beta Pi and a student member of IEEE.

## Facilities and Equipment Data

For the past year, Engineering Research and R-program have funded a low-level research effort (1 FTE) to investigate CT based on current Laboratory radiographic facilities. This work has resulted in two systems; Video Computed Axial Tomography (VCAT)[7] and Multichannel CAT (MCAT)[8] which have respectively demonstrated 100  $\mu\text{m}$  spatial resolution (Video CAT) and quantitative density measurements (Multichannel CAT).[9,10] Although successful research systems, neither provide us with a capability to routinely inspect parts for the various programmatic needs noted above. In addition, to these CT systems we have a complete radiography facility and a microfluorescence lab.

We have recently demonstrated preliminary results in the use of materials constraints to improve image reconstructions quality. We are currently working on the first simple backprojection reconstruction using the SPRINT architecture [5]. Both of these current areas of work will lead into more extensive efforts for FY '88.

Current x-ray sources at LLNL include a fine- and micro- focus x-ray tubes, two linear accelerators (4 MeV and 8 MeV) and various radioisotopic sources (e.g.,  $^{109}\text{Cd}$ ,  $^{241}\text{Am}$ ,  $^{191}\text{Ir}$ ,  $^{60}\text{Co}$ , etc.). The x- or  $\gamma$ -rays are detected using one of several types of detectors. Direct radiation detectors include three intrinsic Ge detectors (two planar and one coax), two Si(Li) detectors and several NaI(Tl) crystals. Indirect radiation is performed using a linear array Si(Li) diode and a 2D array CCD with variable integration rates.

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